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Eric C. Brevik
Iowa State University

Jaehoon Lee
Iowa State University

Thomas E. Fenton
Iowa State University, tefenton@iastate.edu

Robert Horton
Iowa State University, rhorton@iastate.edu

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The Influence of Soil Water Content, Calcite Content, and Temperature on Bulk Electrical Conductivity

ERIC C. BREVIK[1,2], JAEHOON LEE[1,3], THOMAS E. FENTON[1] and ROBERT HORTON[1]

[1]Agronomy Department, Iowa State University, Ames, Iowa 50011
[2]current address: Department of Physics, Astronomy, and Geosciences, Valdosta State University, Valdosta, Georgia 31698-0055
Corresponding author, e-mail: ecbrevik@valdosta.edu
[3]Current address: Biosystems Engineering and Environmental Science, University of Tennessee, Knoxville, Tennesee, 37901-1071

Electrical conductivity (EC) as measured by the Geonics® [a] EM-38 has shown promise as a soil survey tool. EC is determined by a combination of soluble salts, clay content and mineralogy, water content, and temperature. While investigating use of the EM-38 for soil survey purposes, it is important to understand the relative contribution of each of these variables to EC. A laboratory experiment was set up to deteermine the relative influence of water content, temperature, and calcite content on EC using time-domain reflectometry (TDR) probes. TDR was used as a proxy for the EM-38 because of the large volume of soil (at least 1 m^3) needed to conduct such an experiment with the EM-38. Loess leached of carbonate minerals was air-dried and crushed to pass through a 2-mm sieve to provide a uniform base material. Water and calcite combinations were prepared consisting of five water (air dry, 15, 20, 25, and 30% gravimetric) and four calcite content (0, 10, 20, and 30% by weight) treatments. Bulk EC was determined for each of these combinations at five temperatures (10, 15, 20, 25, and 30°C). Water content accounted for 70 to 78% of the variability in EC when calcite content was held constant and for 70% of the variability across all calcite contents. Multiple regression analysis showed the regression coefficient for water content was at least two orders of magnitude greater than the regression coefficients for calcite content and temperature and up to 79% of the variation in EC could be explained using multiple regression.

INDEX DESCRIPTORS: TDR, EM-38, soil electrical conductivity.

Bulk soil electrical conductivity (EC), as measured by electromagnetic induction (EM) using the Geonics® EM-38, has been investigated as a soil survey tool in many parts of the American Midwest (Jaynes et al. 1993, Doolittle et al. 1995, Jaynes 1995, Jaynes 1996a, Jaynes 1996b, Fenton and Lauterbach 1998, Brevik et al. 2000, Brevik and Fenton 2003). Most of these studies have compared soil EC patterns to Order 1 or 2 soil surveys, without investigating the factors controlling soil EC. If EM techniques are to be used in soil mapping, it is important that various factors that may influence soil EC be evaluated.

The manufacturer of the EM-38 has reported that the EC of soil is determined by a combination of soluble salts, clay content and mineralogy, soil water content, and soil temperature (McNeill 1980). Studies available in the soil science literature typically look at only one of these factors, such as soil water content (Sheets and Hendrickx 1995, Khakural et al. 1998), soil salinity (Williams and Baker 1982, Wollenhaupt et al. 1986, Lesch et al. 1992, Nettleton et al. 1994, Lesch et al. 1998), or soil temperature (Brevik et al. in press). Williams and Hoey (1987) looked at two factors, the salt and clay content of soil, while Hanson and Kaita (1997) looked at soil salinity and water content. In each case, these studies found good correlation between the factor being studied and soil EC readings, often reporting r^2 values of 0.7 or greater. However, if the EM-38 is to be used as a soil survey tool, we need to understand the relative importance of the influence of these various factors on soil EC in the soils we work with. Brevik and Fenton (2002) conducted field research along a Mollisol catena in central Iowa in an attempt to quantify some of these relationships. However, controlled laboratory experimentation looking at the factors that influence soil EC, and particularly the factors that do so in Iowa soils, is still desirable.

Unfortunately, it is impractical to use the EM-38 for laboratory studies because of the large volume of soil (a minimum of approximately 1 m^3) that would be needed for each treatment. In addition, it is possible that electromagnetic sources such as electrical systems would interfere with EM-38 readings taken inside a building. Still, laboratory studies of soil EC are desirable because of the ability to control conditions in a laboratory setting. Soil EC can also be determined using time-domain reflectometry (TDR) probes (Dalton et al. 1984, Noborio et al. 1994) in a much smaller volume of soil than that required by the EM-38. Therefore, this study was designed to investigate the influence of soil water content, temperature, and calcite content on bulk soil EC using TDR. The influence of clay on EC was not investigated.

METHODS

This study used 0.002 m diameter 0.15 m long TDR probes (Campbell Scientific Inc., Logan, UT), a cable tester (Model 1502B, Tektronix, Redmond, OR) and TACQ program (Evett 1998) to obtain bulk EC of the soil material. The TDR probes were imbedded in soil material sealed in 0.0016 m^3 plastic containers. TDR probes actually measure the resistive impedance load of the soil material, from which EC can be calculated as described by Wraith et al. (1993) (done in the TACQ program). It is important to note that the ab-

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[a]Trade names are given for the sake of completeness and do not imply recommendation or endorsement by Valdosta State University, the University of Tennessee, or Iowa State University. Journal Paper No. J-19327 of the Iowa Agriculture and Home Economics Experiment Station, Ames, IA, Project No. 3934, and supported by Hatch Act and State of Iowa.

Table 1. Selected properties of the loess base material used for this experiment.

Property	n	Average (%)	Minimum (%)	Maximum (%)	Standard Deviation (%)
Sand	15	3.10	2.60	3.90	0.40
Silt	15	66.20	64.80	67.80	0.90
Clay	15	30.70	29.40	32.30	0.80
pH	15	6.10	6.00	6.20	0.02
Hygroscopic Water (gravimetric)	15	5.68	5.43	5.93	0.18

solute EC values determined from this study are not the same EC values that would be determined by the EM-38 for soils with the same clay, temperature, water and calcite contents because the EM-38 and the TDR probes operate at different frequencies. However, the TDR probes allowed us to measure the relative influence of soil water content, calcite content, and temperature on EC, and it was assumed that these relative values would also hold true for the EM-38 in similar soils.

A uniform base material was needed for this experiment. Loess that had been leached of carbonate minerals was collected from the B hotizon of an exposure in a quarry run by Wendling Quarries, Inc. near Le Grand in Tama County, Iowa to serve as the base material. Loess is a good base material for this study because it is the single most common parent material for Iowa soils (Simonson et al. 1952), and the loess from any single given location generally has uniform properties. The loess was air dried and crushed to pass through a 2-mm sieve. To establish the uniformity of the loess, particle size analysis was performed using the sieve and pipette method as described by Walter et al. (1978) and pH was determined using a 1:1 water dilution (Soil Survey Staff 1996) on 15 samples randomly selected from the bulk loess (Table 1). The air-dried loess was also oven dried to determine the gravimetric hygroscopic water content (Table 1).

A total of 20 different water and calcite combinations were prepared, consisting of five soil water and four calcite content treatments. Each container was packed with 1840 g of air-dry loess or loess-calcite mix to a common height of 0.5 cm below the top of the container to maintain a constant bulk density of 1.2 g/cm^3. The soil water treatments were prepared by adding the appropriate amount of water to the top of each treatment with a graduated cylinder such that the water infiltrated as evenly as possible. Treatments were prepared to be air dry, 15, 20, 25, and 30% water as determined gravimetrically. Calcite contents were 0, 10, 20, and 30% by weight. Bulk soil EC was then determined for each of these 20 moisture and calcite combinations at four different temperatures (10, 20, 30, and 40°C). The range of temperatures used in this study should not significantly affect the TDR instrumentation as it is used to determine electrical conductivity values (Persson and Berndtsson 1998), therefore observed EC differences should be due to changes in the soil material properties.

Calcite was used as the soluble salt in this experiment because it is the most common soluble salt in Iowa soils (Troeh and Thompson 1993). The calcite source used was fine-ground SuperCal 2000, an agricultural lime. At least 95% of this lime passes through a 100 mesh sieve and 90% through a 200 mesh sieve. The manufacturer guarantees the lime to be at least 98% $CaCO_3$. To attain the various calcite treatments used in this study, appropriate masses of SuperCal 2000 and air-dried loess were hand-mixed in a plastic bucket until the mixture displayed a uniform color. The loess-calcite mixture was then packed into a plastic container with a TDR probe. De-ionized water was used to bring each treatment to the desired water level. Although the use of de-ionized water could lead to the loss of some aggregation within the loess, adding a salt solution would alter the treatments' EC by adding a variable not otherwise accounted for in the experiment and not accounted for in any way in the air dry treatments. A growth chamber was used to control temperature at the desired setting, ±0.5°C, during the experiment. The treatments were allowed to equilibrate for 24 hours after each temperature change before EC readings were taken. Statistical analyses were conducted using SAS (SAS Institute, Cary, NC).

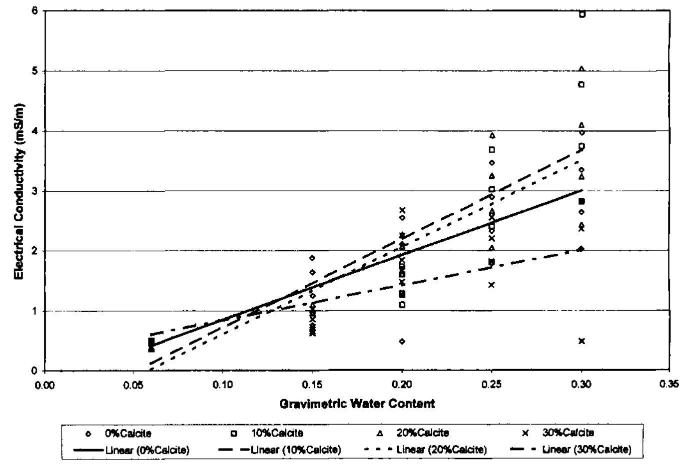

Fig. 1. Soil EC values as a function of gravimetric water content holding calcite content constant, and the best-fit linear regression line for each calcite content.

RESULTS AND DISCUSSION

Results from this experiment were looked at in a number of ways. Simple linear regression was performed on the data to investigate how much of the variation in soil EC readings could be explained by variations in soil water, holding calcite constant and allowing temperature to vary (Fig. 1). The following equations resulted from that analysis:

$$0\%\ \text{calcite} \qquad y = 10.8x_1 - 0.23 \qquad (1)$$

$$10\%\ \text{calcite} \qquad y = 14.9x_1 - 0.78 \qquad (2)$$

$$20\%\ \text{calcite} \qquad y = 14.6x_1 - 0.86 \qquad (3)$$

$$30\%\ \text{calcite} \qquad y = 9.6x_1 - 0.17 \qquad (4)$$

where x_1 is gravimetric soil water content. The r^2 values and other statistics for equations 1–4 are given in Table 2. The range of r^2 values matches up fairly well with r^2 values determined for field sites by Brevik (2001). At five sites, Brevik (2001) obtained r^2 values between 0.51 and 0.91 when regressing soil EC, determined with an EM-38, against gravimetric water content, with four of the five sites having r^2 values between 0.71 and 0.91.

Table 2. Statistics from the moisture simple regression model, holding calcite constant in each case.

Calcite (%)	n[a]	r^2	P-value for the Model	P-value, Regression Coefficient	P-value, Intercept
0	19	0.70	0.0001	0.0001	0.52
10	16	0.70	0.0001	0.0001	0.20
20	20	0.78	0.0001	0.0001	0.04
30	18	0.75	0.0001	0.0001	0.52

[a]n does not equal 20 in all cases because of TDR probe failures

Multiple linear regression analysis was then performed to investigate the additional contribution of soil temperature in explaining variations in soil EC, again holding calcite constant. The following equations resulted from that analysis:

0% calcite $$y = 10.8x_1 + 0.024x_2 - 0.84 \quad (5)$$

10% calcite $$y = 14.9x_1 + 0.047x_2 - 1.97 \quad (6)$$

20% calcite $$y = 14.6x_1 + 0.040x_2 - 1.86 \quad (7)$$

30% calcite $$y = 9.6x_1 + 0.022x_2 - 0.79 \quad (8)$$

where x_1 is soil gravimetric water content and x_2 is soil temperature (°C). The r^2 values and other statistics for equations 5–8 are given in Table 3. This regression was done because soil water content and soil temperature are the two factors that both influence soil EC and vary at any single given position on the landscape over time. In each case, the regression coefficient for the contribution of soil water content to the soil EC determination is at least two orders of magnitude greater than the regression coefficient for temperature, indicating that soil moisture has a larger influence on soil EC than soil temperature. However, the r^2 values are higher when temperature is included in the regression equation (compare r^2 values in Table 2 to those in Table 3).

All the soil EC data were lumped together and regression analysis performed. With calcite values ranging from 0 to 30% by weight and temperature values ranging from 10 to 40°C, simple linear regression was performed to see how much of the variation in soil EC could be explained by changes in soil water content alone, giving the following equation:

$$y = 12.8x_1 - 0.56 \quad (9)$$

Even under these conditions, soil water content explained 70% of the variation in soil EC readings. Stepwise multiple linear regression was performed to investigate how much of the variation in soil EC could be explained by changes in soil water content and temperature and to see what the relative contribution of each of these variables was to the change in soil EC. The following equation resulted:

$$y = 12.8x_1 + 0.03x_2 - 1.4 \quad (10)$$

When stepwise multiple regression was used to see how much variation in soil EC could be explained by changes in soil water, temperature, and calcite content, the following equation resulted:

$$y = 12.8x_1 + 0.03x_2 - 0.01x_3 - 1.3 \quad (11)$$

where x_1 is soil gravimetric water content, x_2 is soil temperature, and x_3 is calcite content. Statistics for equations 9–11 are given in Table 4. The regression coefficient for soil water content was over 2 orders of magnitude greater than the regression coefficient for temperature, a finding that is consistent with the analysis discussed previously when calcite content was held constant. This finding is also consistent with a field experiment conducted by Brevik and Fenton (2002) using an EM-38 to investigate the relative influence of soil moisture, temperature, clay content, and calcite content on soil EC. Approximately 79% of the variation in soil EC is explained by changes in soil water and temperature.

As with temperature, the regression coefficient for the contribution of soil water content to the soil EC was over two orders of

Table 3. Statistics from the moisture and temperature multiple regression model, holding calcite constant in each case.

Calcite (%)	n	r^2	P-value for the Model	P-value, Regression Coefficient (Soil Water)	P-value, Regression Coefficient (Temperature)	P-value, Intercept
0	20	0.76	0.0001	0.0001	0.045	0.065
10	16	0.81	0.0001	0.0001	0.017	0.009
20	20	0.88	0.0001	0.0001	0.001	0.001
30	18	0.84	0.0001	0.0001	0.012	0.021

Table 4. Statistics for regression the regression models using all data. A total of 74 observations were used in the models represented in this table.

Model[a]	r^2	P-value for the Model	P-value, SW Regression Coefficient	P-value, temp Regression Coefficient	P-value, cal Regression Coefficient	P-value, Intercept
SW only	0.70	0.0001	0.0001	NU	NU	0.008
SW, temp	0.79	0.0001	0.0001	0.0001	NU	0.001
SW, tmp, and cal	0.79	0.0001	0.0001	0.0001	0.33	0.001

[a]SW = soil gravimetric water content, temp = soil temperature, and cal = calcite content, NU = Not undertaken, this regression did not include the indicated coefficient.

magnitude greater than the regression coefficient for the contribution of calcite content in explaining soil EC, indicating that soil water content has a greater influence on soil EC than does calcite content. Brevik and Fenton (2002) report similar findings when using the EM-38 in the vertical dipole. Adding calcite content to the multiple regression equation did not improve the r^2 value of the equation (Table 4).

Calcite content had a negative correlation to soil EC (see Equation 11), a finding also reported by Brevik and Fenton (2002). Among the salts commonly found in soils, calcite has relatively low solubility. Much of the work done using EC to investigate soil salts has been done in arid or semi-arid regions such as Australia (Williams and Baker 1982, Williams and Hoey 1987, Slavich and Petterson 1990, Slavich et al. 1990), North Dakota, USA (Wollenhaupt et al. 1986), California, USA (Lesch et al. 1992, Hanson and Kaita 1997), and Alberta, Canada (Cannon et al. 1994), where salts with greater solubility than calcite are present in the soil profile. The low solubility of calcite relative to other salts may explain the negative correlation to soil EC found in this study and by Brevik and Fenton (2002) when soluble salts have generally been reported to increase soil EC.

CONCLUSIONS

When calcite content was held constant, soil gravimetric water content explained between 70 and 78% of the variation in EC in this experiment. Even when calcite content and temperature were allowed to vary, gravimetric water content explained 70% of the variation seen in EC. Multiple linear regression analysis indicates that the regression coefficient for the influence of soil water content on EC is at least two orders of magnitude greater than the regression coefficients for the influence of soil temperature or calcite content. Therefore, under the conditions studied, soil water content appears to be the major controlling factor of EC. Addition of soil temperature as a variable in the regression equation resulted in greater r^2 values than when only soil water content was considered. However, adding calcite content to the multiple regression equation in addition to soil water and temperature did not result in a higher r^2 value. It is likely that, because of its relatively low solubility in comparison to other salts commonly found in soil, calcite is not a significant factor in determining soil EC.

Soil water content, salinity, and temperature, the factors considered in this study, are factors that commonly change in an ordered, predicable way within the soils on Iowa landscapes. Soil water content is typically lowest in soils at the tops of hills or slopes, and increases as one proceeds downslope. Salinity follows a similar pattern. Soil temperature generally changes more rapidly in dry soils; therefore, more rapid changes in soil temperature would be expected in higher, drier landscape positions than in lower, wetter ones. Because these EC controlling factors vary in a predicable fashion in the field, studies such as this one should help in understanding EC results obtained in the field.

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